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Strategies and resources of mode-division-multiplexed optical fibre transmission based on LP and orbital angular momentum modes

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ABSTRACT

We present research into the capacity and spectral efficiency of various spatial and mode division multiplexed transmission schemes in multimode optical fibres, including MIMO schemes based linearly polarized (LP) modes and orbital angular momentum (OAM) modes. We estimate their spectral efficiency by calculating the transmission matrix and considering mode coupling under different schemes. We also consider the signal-processing prefix for LP-MIMO and OAM based technologies to calculate the effective spectral efficiency. Simulation results show LP-MIMO using step-index fibre can support higher spectral efficiency than both LP-MIMO with graded-index fibre and OAM, while LP-MIMO with graded-index fibre has similar levels of spectral efficiency as OAM. We further compare the computational resources required to support the signal processing algorithms in order to achieve certain amount of capacity or spectral efficiency and reveal the scaling of computational resources with capacity in different MDM schemes. Considering the implementation of MIMO algorithms and any processing required to support spatial light modulator (SLM) based optical crosstalk equalization schemes, we demonstrate that OAM-based MDM has the lowest computational resource requirement and offers a much higher spectral efficiency with limited computational resource in both processing power and memory size requirements resulting from intermodal group velocity dispersion in multimode fibres. We also show that OAM based schemes could save significant signal processing energy overhead due to its low computational resource requirement.

Keywords: spatial division multiplexing, mode division multiplexing, MIMO, multi-mode fibre, OAM communications

1. INTRODUCTION

The capacity of optical fibre communications links has been increasing exponentially over several decades at an average rate of ~15% per annum [1], with occasional revolutionary bursts of growth (such as driven by wavelength division multiplexing - WDM). As the single mode fibre (SMF) capacity approaches the nonlinear Shannon limit, techniques using space division multiplexing (SDM) or mode division multiplexing (MDM) in multi-core or multi-mode fibres have been increasingly investigated in order to provide new degrees of freedom to achieve higher capacity [2].

SDM launches optical signals channels into spatially diverse apertures at the input facet of the fibre and detects the signal at corresponding apertures at the fibre output facet. SDM can be implemented using multi-core fibres (MCF) with spatially parallel cores each supporting own (un-coupled) mode 5. While MCFs with up to 49 cores have been reported [3], evanescent coupling between adjacent cores starts to cause crosstalk. When further closely packed, individual core modes strongly couple to form ‘super-modes’ as the true eigen-modes of the collective waveguide. The extreme case is a merged fibre core supporting a large number of spatially overlapping modes, i.e., a well-known multi-mode fibre (MMF), over which either SDM or MDM can be implemented. In general, each SDM channel will excite all modes supported by the MMF.

MDM selectively launches optical signals channels into individual (or groups of) modes [4] at the input facet, and separate (or de-multiplex) and detect each mode (group) at the output facet. Optical mode (de-)multiplexing is possible due to the by re-establishing their relative phase, given all modes remain orthogonal throughout the length of propagation or knowing their coupling matrix [5].

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Arguments have persisted on the spectral efficiency or capacity that can be supported by these schemes, and their relative potentials of scalability. One theory purports that orbital angular momentum (OAM) as a degree of freedom of photons provides an infinite state space in which communications can be carried out [6]. However, there is a counter-argument that OAM modes are merely a sub-set of all optical modes in both free space and fibre, therefore it must provide no more effective degrees of freedom and hence have no advantage in terms of the supported capacity or spectral efficiency over those schemes utilizing the entire mode space [7].

In this paper, we make a rigorous comparison of the spectral efficiency (SE), signal processing complexity (SPC) between SDM and MDM communications schemes using various kinds of optical fibres supporting OAM and LP modes, aiming at clarifying these arguments and map out the potential capacity resources available to be exploited, as well as the optimum ways of exploitation in terms of cost, power consumption and practicality.

2. THEORETICAL MODELS

2.1 Spectral Efficiency

In practical MMFs, coupling between modes is inevitable due to perturbations, e.g., core-cladding interface roughness, bending, squeezing, etc., [8]. Mode coupling gives rise to signal channel crosstalk noise therefore reduces channel capacity according to Shannon's Theorem. Signal channels in SDM are spatial apertures whereas in MDM are the modes themselves.

Signal processing may be used to suppress crosstalk noise and recover the information transmitted[9], at a cost of additional hardware, software and energy consumption. A well-established body of signal processing methods has been developed for wireless systems with MIMO ports[10], which has also been widely used in SDM and MDM schemes [11], and already deployed in 100G coherent systems. A MIMO system over MMF with N transmitters, N receivers and additive noise can be written as $r = Hx + n$, where H is the normalized channel matrix, n is the noise, r is the received signal and x is the transmitted signal. We assume the channel matrix is known at the receiver, by using singular value decomposition, the spectral efficiency (SE) of the fibre link can be generalized as [12]

$$SE = \sum_{i=1}^N \log_2 \left(1 + \lambda_i \frac{\rho}{N} \right) \text{ (b/s/Hz)} \quad (1)$$

where $\sqrt{\lambda_i}$ is the singular value of normalized channel matrix H , ρ is the average signal-to-noise-ratio (SNR) independent of channel count N .

The channel count N and channel matrix H are highly dependent on the launch schemes (SDM or MDM), the mode-set of the fiber, and the mode coupling behavior in the fibre. Three kinds of cylindrical multi-mode fibres (MMF), the Step-Index Fibre (SIF), the Graded-Index Fibre (GIF), and the Ring Core Fibre (RCF), are commonly investigated for both SDM and MDM schemes. In MDM schemes, the supported channel count N equals to the number of modes N_M in the fibres. The highest supported SDM channel count in SIF and GIF is $4N_M$ [13]. N_M is the number of linearly polarized ($LP_{m,l}$, m and l are the radial and azimuthal mode indices) modes supported by the fibre. $N_M = V^2/2$ for SIF and $N_M = V^2/4$ for GIF [14], $V = k_0 a \sqrt{n_1^2 - n_2^2}$ is the normalized frequency of the fibre with core radius a and the core and cladding refractive index (RI) values of n_1 and n_2 . In SIF, the effective RI n_{eff}^i values of the modes can be treated as evenly distributed between n_1 and n_2 , and power couples from a mode to the other modes according to Δ . For large fibre core size, the n_{eff} values form a near-continuum and optical power launched into one or a small number of modes diffuses through this continuum of modes to reach all modes. In a GIF with parabolic refractive index (RI) profile, degenerate groups containing $M = 2m + l$ modes are separated by a large constant Δn_{eff} , therefore with little inter-group coupling. Inside each group, modes couple strongly due to their degeneracy.

RCFs have ring-shaped cores with low-high-low radial RI profiles from center to cladding designed to support only one radial mode ($m=1$). For $|l| > 0$, near-degenerate ($LP_{1,l}$) mode groups can be formed each containing a fixed number of 4 eigen-modes (the $EH_{l-1,1}$ and $EH_{l+1,1}$ modes X 2 polarizations). RCF has been designed to support SDM [15]. The maximum SDM channel count supported is $2MAX(|l|)$. RCFs can be designed to lift the degeneracy between eigen-modes (the $EH_{l,1}$ and $HE_{l,1}$ modes) in the same mode group [16], so that each mode group contains 4 (four) OAM modes, formed as follows:

$$\begin{aligned} OAM_{\pm l, m}^{R, L} &= HE_{l+1, m}^{even} \pm jHE_{l+1, m}^{odd} \\ OAM_{\mp l, m}^{L, R} &= EH_{l-1, m}^{even} \pm jEH_{l-1, m}^{odd} \end{aligned}$$

where the R, L in the superscript denotes the right- or left-handed circular polarization, l being the OAM topological charge, and its sign denotes the wave-front rotation direction. For mode-group $l=0$, only two $LP_{1,0}$ modes (TE & TM polarized) or two OAM modes (OAM_0^R and OAM_0^L) exist. RCF Mode groups are also well separated with linearly increasing Δn_{eff} for larger $|l|$. The OAM modes have left- or right- circular polarization. The polarization can rotate either in the same directions of or opposite to the phase front rotation.

Mode-coupling between a pair of modes is governed by the power coupling factor (PCF) of $\frac{2\kappa^2}{4\kappa^2 + \Delta^2}$ [17], where κ is a coupling coefficient determined by the physical perturbation of fibre. $\Delta = \frac{2\pi\Delta n_{eff}^{ij}}{\lambda}$ is the phase mismatch between the i^{th} and j^{th} modes decided by $\Delta n_{eff}^{ij} = n_{eff}^i - n_{eff}^j$ the difference between their effective RI.

Due to their very different modal characteristics, the mode coupling process and therefore the signal processing strategies for SIF-, GIF- and RCF-fibre based SDM and MDM schemes can be very different.

Full $N \times N$ MIMO is required for all SDM schemes as all modes are excited by the spatial aperture launch. SIF-MDM scheme also requires full $N \times N$ MIMO due to extensive mode coupling between modes in SIF. However, for GIF- and OAM-MDM schemes, the channels are launched into modes. Because there is little coupling between mode groups, it is possible to reduce the MIMO processing, applying it only to modes within the same mode group. Therefore, GIF-MDM would only require $M \times M$ MIMO ($M = 2m + l + 1$ being the number of mode channels in each mode group). For OAM-MDM in RCF, $M \equiv 4$ and the total number of 4×4 MIMO modules is $(N_{OAM} - 2)/4$. Mode group $l=0$ only needs to be processed by a 2×2 MIMO. The fixed MIMO size can be a major attraction for practical implementation as the signal processing chip can be standardized.

In MMFs, due to the complicated mode coupling processes, not all SDM or MDM channels have the same SNR. Instead of launching the same signal power into each channel, we use a more efficient ‘water-filling’ algorithm that allocates signal power optimally amongst channels to achieve higher overall SE, the improved SE equation can be obtained as [12, 18]

$$SE = \sum_{i=1}^N \log_2 [1 + \frac{1}{\sigma^2} (\lambda_i \mu - \sigma^2)^+] \text{ (b/s/Hz)} \quad (2)$$

where a^+ denotes $\max(a, 0)$, σ^2 is the receiver noise variance and μ is the required water-filling power level.

2.2 Signal Processing Complexity

We assume the use of adaptive frequency-domain equalization (FDE) with fast Fourier transform (FFT), which is considered the most efficient approach to realizing MIMO digital filtering algorithms[19] because it converts time domain convolutions into frequency domain multiplication. The SPC of FIR filter based FDE can therefore be measured by the number of complex multiplications per channel per second, given by [11]

$$SPC = \frac{(4+2N) \cdot C_{rad} N_{FFT} \cdot \log_2(N_{FFT}) + 2N \cdot N_{FFT}}{(N_{FFT} - N_{MD} + 1)} R_s \quad (3)$$

where $C_{rad}=0.5$ for a radix-2 FFT and $N_{FFT} = 2^{\lceil \log_2(2 \cdot N_{MD}) \rceil}$ the FFT block length. In order to realized adaptive filter update, Overlap-save FFT can be adopted to avoid cyclic prefix which may decrease net throughput. We assume radix-2 FFT and 50% overlap-save. N_{MD} is the number of sampling points that has to be stored due to the group velocity dispersion between modes that dictates the number of filter taps for each equalization block. N_{MD} decides the amount of filter memory size that will be needed, which is also a contributing factor to hardware cost.

3. RESULTS

We assume the three kinds of optical fibers have the same RI contrast of $n_1 - n_2 = 0.03$. We calculate the spectral efficiency and signal processing complexity for a 1 km SDM or MDM link implemented on each kind of fibre. We also consider a range of fibre radii of 10, 20 and 50 microns.

3.1 Spectral Efficiency

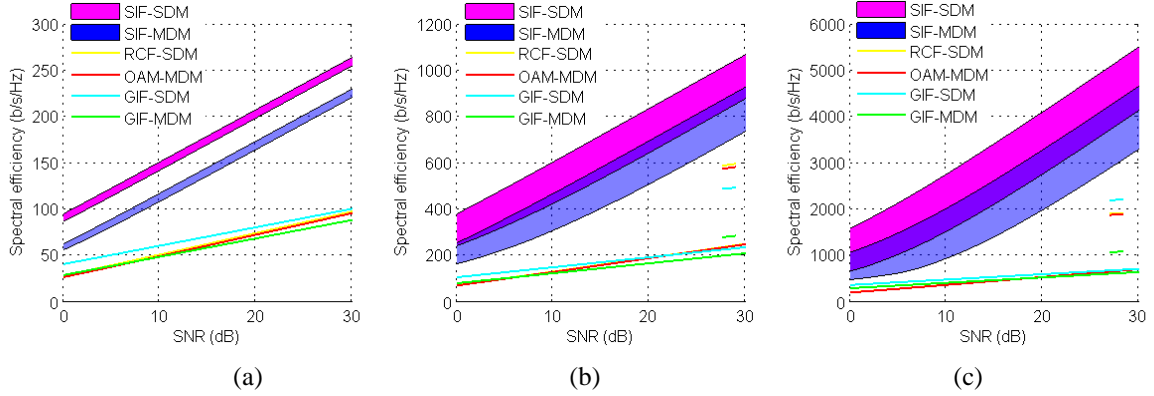


Figure 1. Spectral efficiency for different SDM and MDM schemes implemented on fibres with (a) core radius = 10 μm , (b) 20 μm , and (c) 50 μm .

In Figure 1, comparisons of the theoretically spectral efficiency of SDM and MDM schemes supported by difference fibres are plotted against the average SNR as defined in Eq.(1). For the SIF based SDM/MDM schemes, we calculate an upper and a lower spectral efficiency boundary. These are respectively determined by the low and high mode coupling, i.e., value of $\kappa = 40.5 \text{ km}^{-1}$ and 324.3 km^{-1} , as high coupling leads to low channel spectral efficiency. It can be seen that, at moderate to high SNR, SIF can theoretically support 5-10 times higher spectral efficiency over other schemes because it has the largest number of channels (also see Figure 2(c)). The difference between the SDM and MDM is because of the 4x more channels supported by SDM. For GIF based MDM, RCF based SDM, and RCF based OAM-MDM schemes, the calculated SE values are quite similar to each other. At fibre radius of 20 μm which is close to commercially available MMFs (such as OM4 fibre), they all support spectral efficiency of $>100 \text{ b/s/Hz}$ for moderate SNR, which is significantly higher than the nonlinear Shannon limit of $\sim 10 \text{ b/s/Hz}$ in standard SMF. These values are calculated assuming very strong coupling within mode groups so that all input channels end up diffusing uniformly over all modes, therefore represent conservative estimations. It can therefore be claimed that all schemes provide significant potentials for capacity upgrades over SMF.

3.2 Signal Processing Complexity and Hardware Resources

We calculate the signal processing complexity and hardware requirements by further assuming the data channels has a symbol rate of 32 GBaud, and the SDM and MDM schemes are populated by such channels until the spectral efficiency as plotted in Figure 1 is fully utilized. The modulation format for each data channels is 16QAM.

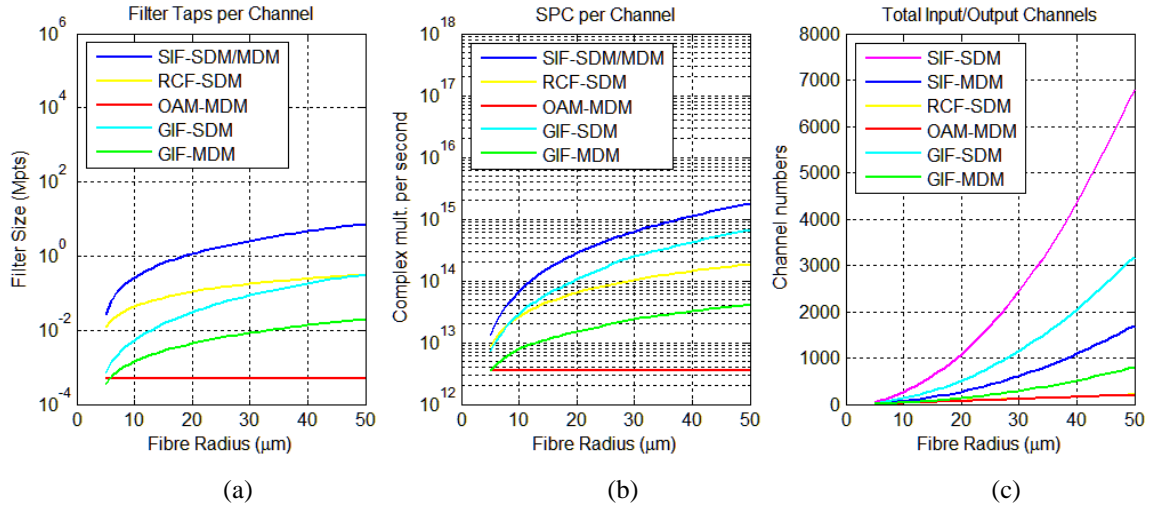


Figure 2. (a) Total memory size requirement, (b) Multiplications per second for FDE, and (c) Total Channel Numbers

In Figure 2 (a), the number of sampling points to be stored for the FIR FDE filter (equivalently, the filter tap number) is plotted for all the schemes. SIF based schemes require large memory because of the large dispersion between all the modes that need to be processed. For the other two fibres, the mode-group based processing reduces the memory size due to the near-degeneracy within mode groups. OAM-MDM need very small memory.

Figure 2(b) plots the number of multiplications per second that have to be performed in the FDE as a measure of the signal processing complexity. A difference of two orders of magnitude is observable between the most (SIF) and the least (OAM MDM) processing intensive schemes at the fibre radius of 20 μm while the number of effective channels supported is only different by a factor of ~ 6 (Figure 2(c)).

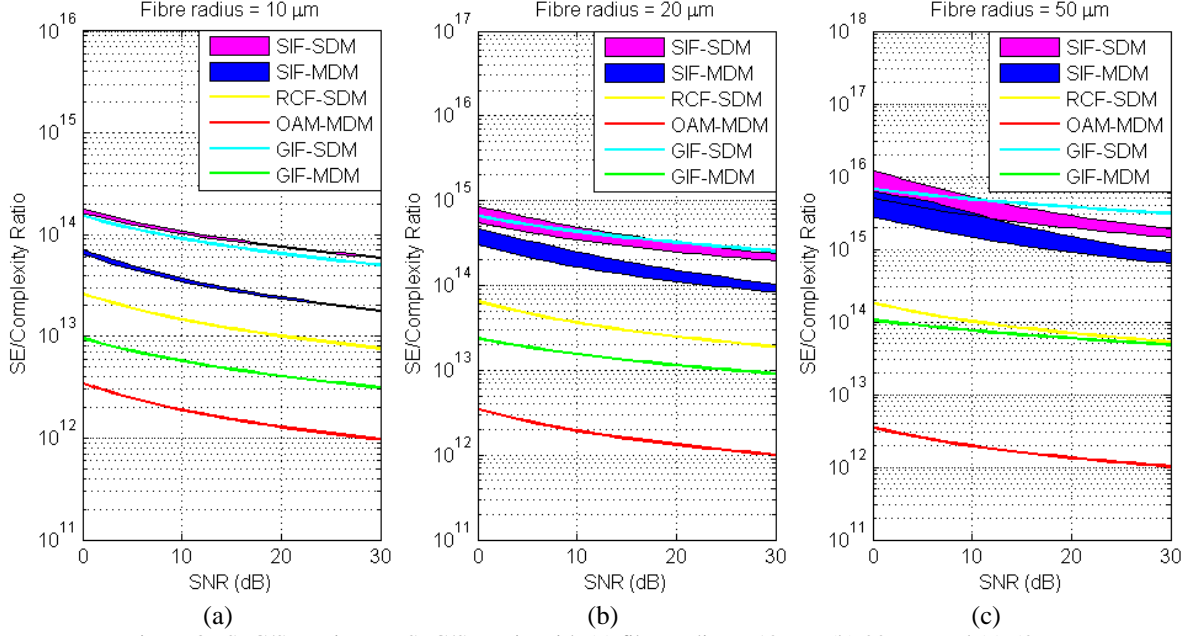


Figure 3. SPC/SE ratio. a-c, SPC/SE ratio with (a) fibre radius = 10 μm , (b) 20 μm , and (c) 50 μm .

To make a fair comparison, it is useful to take the ratio of signal processing complexity over the supported spectral efficiency, which means the amount of processing needed to support a unit of spectral efficiency. The results are plotted in Figure 3 and clearly shows the advantage of OAM MDM over the other schemes in terms of its cost effectiveness and practicality, which is 2 orders of magnitude more resource-efficient than SIF schemes for fibre radius of 20 μm . An interesting comparison can also be found between SDM and OAM MDM schemes based on the same RCF. They provide virtually the same number of effective channels but SDM requires 1.5 orders of magnitude more processing resources due to the fact that it involves all modes for each SDM channel. This highlights the importance of utilizing the orthogonality between modes or mode groups to minimize processing.

3.3 Quantitative Estimations and Benchmarking

Quantitative estimations can be made for 20 μm fibre core radius and modest SNR of 20 dB. This supports theoretical SE of 190 (OAM-MDM) and 836 (SIF-SDM) b/s/Hz, a difference of only about 4x. To achieve the theoretical SE by multiplexing 32 GBaud data channels, however, SIF-SDM needs 1.26 Giga-points filter memory and 2.08×10^{17} multiplications per second. In comparison, OAM-MDM only needs 34.5 kilo-points memory and 2.5×10^{14} multiplications per second.

The signal processing complexity values can be benchmarked against commercially available high processing power FPGAs. For example, the Xilinx VIRTEX-7 is capable of 5.335 Tera-MACS (multiplications and accumulations) per second with 40-W power consumption. To achieve their respective theoretical spectral efficiency, SIF-SDM needs processing power equivalent to 38988 FPGAs that would consume 1.56 MW of power, while OAM-MDM only need 47

and 1.88 kW. The signal processing energy overhead is 0.309 and 58.3 nJ/bit for OAM-MDM and SIF, respectively. On the other hand, to achieve a spectral efficiency equal to the SMF nonlinear Shannon limit of 10 b/s/Hz with 32 GBaud channels, OAM-MDM only need 3 FPGAs at 120 W, while SIF-SDM need 468 FPGAs at 18.72 kW. The energy overhead is 0.375 and 58.5nJ/bit for OAM-MDM and SIF, respectively. DSPs may be optimized for FDE algorithms to achieve further reduction in energy consumption. As an indication, commercially available MIMO DSPs (NTT ExaSpeed200) optimized for optical communications can reach 0.05nJ/bit (10W for 200 Gb/s), and are almost directly applicable to OAM MDM to implement the 4x4 MIMO blocks.

4. CONCLUSION AND DISCUSSION

Based on above calculations, it can be concluded that among the spatial and mode divisions multiplexing schemes for multimode optical fibre communications, SIF based SDM and MDM schemes supports the highest theoretical spectral efficiency. However, to fully utilize their potentials requires unrealistic signal processing powers and very large filter memory size due to the need to process a full MIMO matrix with large group delay. It also requires far higher signal processing complexity and memory size to utilize a certain SE compared to GIF- and OAM-MDM. In contrary, for a given MIMO equalizer with limited processing circuitry and memory, OAM-MDM can achieve the highest SE. It is also able to reach SE values significantly above existing technologies with realistic signal processing hardware and power consumption based on (4x4) MIMO DSPs. The fixed MIMO size of 4x4 can be a major attraction for practical implementation as the DSP can be standardized for modular upgrades, and as pointed out above, DSPs of similar complexity is already available. OAM-MDM therefore represent the most practically scalable MIMO scheme in optical fibres.

It should be noted that for GIF- and OAM-based MDM, the assumption that the mode groups are not coupled can only be valid to a certain extend. Usually this requires Δn_{eff} of $> 1 \times 10^{-3}$ between mode groups. Existing commercial fibre technologies can produce $n_2 - n_1$ of ~ 0.03 . For GIF of $a = 20 \mu\text{m}$ this can supports about 30 mode groups that satisfies the condition of $\Delta n_{eff} > 1 \times 10^{-3}$ with about 150 modes. For RCF it can supports about 10 groups with 40 modes. Novel fibre technologies reported have produced much higher $n_2 - n_1$ thereofre can support more mode channels while maintaining low coupling between mode groups [20]. In fact, zero coupling is not feasible, but it is possible to recover weak coupling between modes groups by optical means with some optical hardware but only minor requirements on electronic processing.

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